

MARINE CARBON SENSING WORKSHOP: Transformative full-ocean depth sensor platforms

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Current in situ sensor platforms

DRIFTER

Cheap and easily deployed, power in numbers

Cost: \$500-6,000 Depth: 0-100m Motion: Lagrangian

drift

Ex: Sonobuoys, Sofar Spotter





FLOAT (profiler)

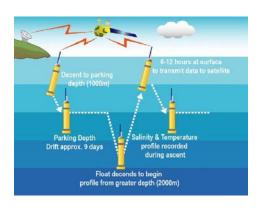
Ability to change depth by adjusting buoyancy or crawling a mooring line

Cost: \$20,000-100,000

Depth: 100-6000m

Motion: Moored or drifting

Ex: Argo program



AUTONOMOUS

Self-powered, steerable, long activity cycle

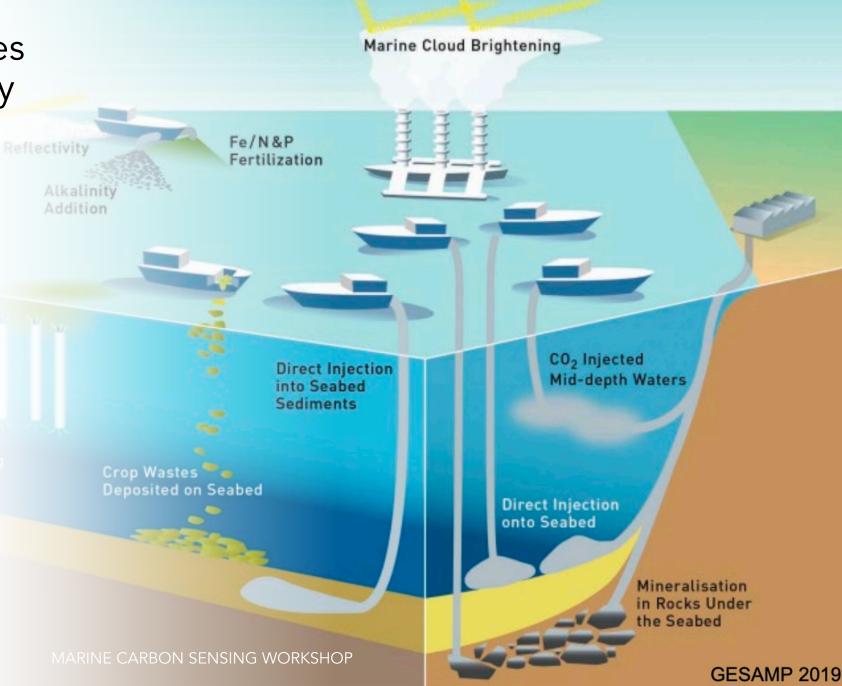
Cost: \$200,000-10,000,000 Depth: 200-1,000m though some have reached 6000m Motion: Pseudo-active

Ex: Wave Glider



Platform technologies critical to successfully measuring and reporting of CO₂

- Measurement Challenges
 - Spatial
 - $10^{-2} \rightarrow 10^2 \text{ km}$
 - Temporal
 - $10^{-3} \to 10^2 \text{ years}$
- Platform Challenges
 - Environment
 - Efficiency/ Cost of Transport
 - Range
 - Energy generation
 - Duration
 - Robustness
 - Economics



Ability to actively/passively monitor carbon levels in <u>all ocean zones</u> will require new solutions in the underwater platform design space

Opportunity to go beyond traditional platform design and take inspiration from biology: manmade underwater vehicles have had ~250 years to evolve, biology... millions of years

DIVERSITY OF DESIGN: 35,000+ species of known fishes occupying all oceanic zones presents incredible morphological diversity

Mother nature offers inspiration

Benthic and Pelagic Zones Intertidal Zone Epipelagic Zone - The Sunlight Zone Continental Shelf 200 Mesopelagic Zone - The Twilight Zone 1 000 Continental Slope Sperm whale **PELAGIC** 2 000 Bathypelagic Zone maximum depth 1 000 m The Midnight Zone **ZONES** 3 000 000 Depth at which Continental Rise Abyssopelagic Zone -The Titanic rests 5 000 3 800 m The Abyssal Zone 6 000 **Hadalpelagic** Ocean Basin - Abyssal Plain Zone - The 7 000 **BENTHIC** Trenches ZONES 8 000 Height of Mount Everest 8 848 m 9 000 **Depth James Cameron** 10 000 reached in 2012 10 898 m 11 000

Biological Propulsion: Diversity of Design & Inspiration

Biology has evolved solutions to inhabit all oceanic zones

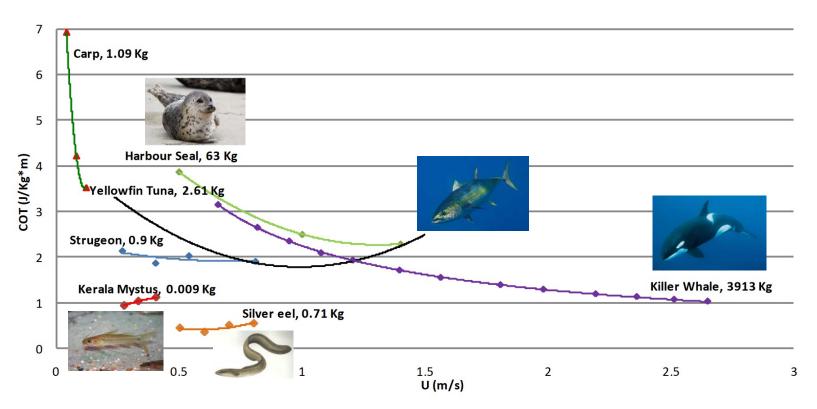
- ➤ Offers the potential for game changing solutions for autonomous platform designs that form the framework to quantifying carbon in the ocean
- Must be clear on what aspects of their solution are critical to success
 - ➤ SPATIAL/TEMPORAL//ENERGETICS/COST/ETC CONSTRAINTS
- > Idea is not to mimic biology but be inspired

Fishes are not pressure vessels

- > IDEA OF DEPTH AGNOSTIC SYSTEMS
 - ➤ Removing pressure vessel design through soft, solid-state components opens up deep ocean zones for MRV
- > ECONOMICS OF SOFT SYSTEMS
 - > Cost less than traditional metal-foam UUV designs

Quantifying Energy Efficiency

Cost of Transport (i.e., energy efficiency): varies with speed and species



- Active metabolic rate of fish is analogous to electrical power consumption of platform ==> cost of transport scaled by body mass (J/kg/m) allows biology-robot comparison directly
- CoT is a key metric to quantify
- Understand recharging requirements for long duration sensing runs
 - Charging stations (analogous to cleaning stations of Manta Rays)

(Phillips et al., 2012, Further Advances in Unmanned Marine Vehicles, edited by G.N. Roberts and R. Sutton ISBN: 978-1-84919-479-2)

Pressure drag

Lift-based propulsion

Acceleration reaction







Biological Propulsion: Diversity of Design & Inspiration

Lift-based propulsion

GhostSwimmer Autonomous Undersea Vehicle (AUV) by Boston Engineering

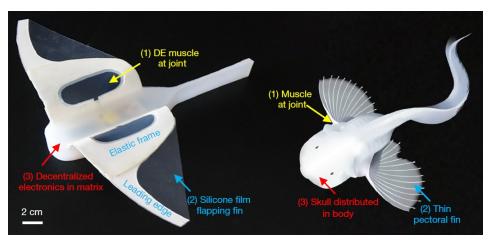
Tuna-inspired

• Maximum depth: 100 m

• Endurance: 14 hrs







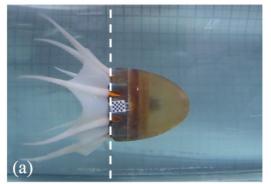
Soft robot (left) inspired by snailfish (right)

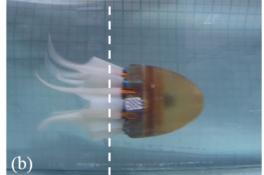
- Swam at depth of 10,900 m in the Mariana Trench
- Actuated by dielectric elastomer (DE) material
- Li et al. Self-powered soft robot in the Mariana Trench, Nature (2021) doi: 10.1038/s41586-020-03153-z

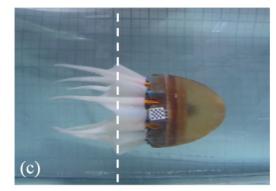


 Cai et al., "Research on Robotic Fish Propelled by Oscillating Pectoral Fins", Robot Fish, 2015 ISBN:978-3-662-46870-8

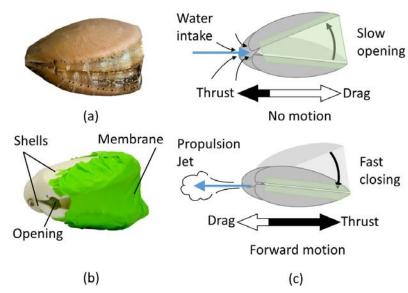
Acceleration reaction

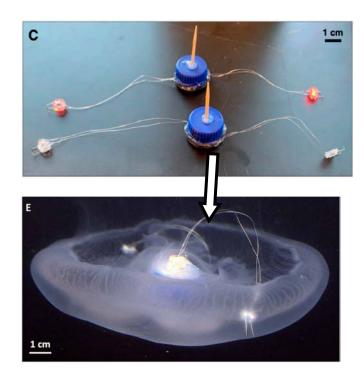






Soft, compliant web made of silicone Sfakiotakis et al. (2014) doi:10.1109/IROS.2014.6942576





- "RoboScallop"
- Powered by a single DC motor
- Robertson et al. (2019) doi:10.1109/LRA.2019.2897144

Low-power microelectronics embedded in live jellyfish enhance propulsion

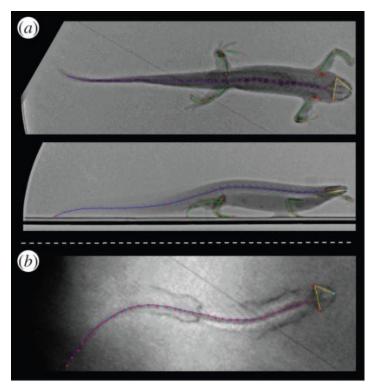
(Xu, ..., **Dabiri** (2020) doi:10.3390/biomimetics5040064) (Xu & **Dabiri** (2020) doi:10.1126/sciadv.aaz3194

Pressure drag

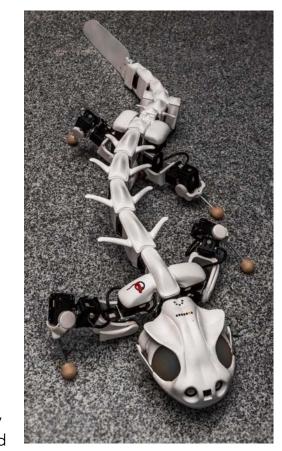


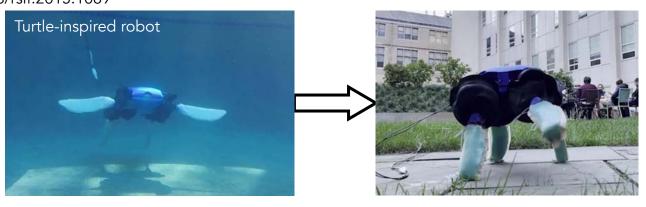
- Turtle-inspired robot using soft material flippers change shape into legs
- Rebecca Kramer-Bottiglio (Yale University), Frank Fish (West Chester University), Simon Freeman (NUWC) (https://www.youtube.com/watch?v=Q9FyaRtLOys)

Amphibious Systems: Land & SeaBased Missions



"Pleurobot": salamander-like robot Karakasiliotis, Thandiackal, et al. (2016), From cineradiography to biorobots: an approach for designing robots to emulate and study animal locomotion, Royal Society Interface doi:10.1098/rsif.2015.1089





Speed and Cost of Transport: Literature Review

Roforonco	Description	Spood (mfs)	Bady Longth BL (m)	Spood (BL/r)	Actuation Frequency (H
Andorson & Chhabra (2002)	VCUUV	1.25	2.4	0.52	1.0
Barrott et al. (1999)	Robotuna	0.70	1.25	0.56	1.1
Borlingor or al. (2021)	Finbat	0.122	0.160	0.763	4.25
Bujardot al. (2021)	Roboticsquid	0.26	0.266	0.98	9.0
Butail et al. (2015)	Roboticzobrafish	0.04	0.154	0.26	3.0
Cai et al. (2010) Cai et al. (2015)	Robo-ray II Robotic coungraray	0.157	0.32 0.46	0.49	1.2 0.6
Chon & Jiang (2019)	Torrogrity robotic firh	0.30	0.420	0.72	1.72
Chon et al. (2015)	IPMC robotic country ray	0.007	0.21	0.034	0.157
Chon et al. (2019)	IPMC robotic firh	0.12	0.27	0.45	1.0
Chon ot al. (2021)	Leaping firh bot	1.88	0.264	7.12	15.04
Christianson et al. (2018)	DEA robatic loptacophali	0.0019	0.22	0.0086	0.33
Christianson et al. (2019)	DEA robotic jelly fish	0.0032	0.163	0.020	0.2
Cianchotti ot al. (2015)	OCTOPUS	0.05	0.17	0.3	0.75
Curot ot al. (2011)	Robotic knifefirh	0.30	0.459	0.65 1.52	6.0
Du et al. (2019)	CariTuna	0.80	0.52		5.0
Erturk (2015)	MFC piozaoloctric firh	0.075	0.243	0.31	5.0
Faridoddin Maroomi ot al. (2014) Firh ot al. (2017)	UC-Ika 1 MantaBot	0.29	0.70 0.428	0.41 1.00	3.0 1.1
Funotal.(2017) Fujiwara®Yamaquchi(2017)	Mantabat Single-mater-actuated firh	0.43	0.428	1.7	16.0
Gibouin et al. (2018)	Flexible rabatic firh	0.104	0.17	0.61	1.6
Hirata et al. (2000)	Roboticzoabroam	0.20	0.34	0.59	2.3
Jurufi et al. (2017)	Pneumaticsuimmer	0.13	0.17	0.75	0.55
Katzrchmann et al. (2018)	SoFi	0.235	0.47	0.50	1.4
Kumph (2000)	Robopiko	0.09	0.82	0.1	1.0
Kuak & Bae (2017)	Roboticustorbootlo	0.117	0.095	1.2	1.3
Loftwich & Smitr (2011)	Roboticlamproy	0.115	1.14	0.10	0.55
Loftwich et al. (2012)	Roboticlamproy	0.10	0.90	0.11	0.56
Li et al. (2013)	Underactuated robotic firh	0.15	0.425	0.35	1.0
Li et al. (2017)	Electra-ianic rabatic fürh	0.135	0.093	1.5	5.0
List al. (2019)	Group of robotic firk	0.575	0.45 0.22	1.28 0.24	1.4
Li et al. (2021) Lian et al. (2014)	Mariana Tronchsoft robot Wiro-drivon robotic fish	0.0519	0.495	0.67	1.0 1.0
Lia@otal.(2014) Liu&Curot(2018)	Wire-ariven rabatic run KnifeBat	0.335	0.462	0.703	3.0
Langet al. (2006)	BEAsuimmer	0.069	0.33	0.21	1.7
Lang Jr. et al. (2006)	Madeleine	0.74	0.78	0.95	6.0
Maxlan (2015)	Robaralmon	0.143	0.90	0.16	1.0
Mazumdar et al. (2008)	Compliant Robotic Tuna (CRT)	0.10	0.27	0.37	2.0
McGavernet al. (2009)	NEMO-propolled firk	0.033	0.125	0.26	0.8
Mahammadrhahi et al. (2008)	ADCSL robotic firk	0.75	0.6	1.25	4.0
Nooly ot al. (2016)	Roboticstingray	0.094	0.35	0.27	1.4
Parchaletal. (2017)	Reconfigurable armed robot	0.1	0.6	0.2	2.0
Pham et al. (2019)	Postaral fin-propolled firh	0.231	0.4	0.58	0.75
Robertron et al. (2019)	RoboScallop	0.16	0.8	0.20	2.56
Sfakiotakir et al. (2015) Shao & Xu (2019)	Rabatic actopur MFC piezaelectric fürh	0.0986 0.1645	0.38 0.345	0.26 0.48	0.9 14.0
Shintako otal. (2018)	DEA robotic firh	0.0372	0.15	0.25	0.75
Shintako et al. (2020)	Tonrogrity trautrabat	0.23	0.400	0.58	3.0
Tan ot al. (2006)	IPMC robotic fish	0,0063	0.23	0.03	2.0
Valdivia y Alvarado & Youcof-Toumi (2015)		nfa	nta	0.579	5.0
Villanuova ot al. (2011)	Robojelly	0.0542	0.6	0.1	0.5
Villanuova ot al. (2013)	Cyro	0.0847	0.316	0.268	0.12
Wang ot al. (2010)	SPC-3UUV	1.87	1.6	1.2	2.5
Wangotal. (2019a)	Broartrako-irapirodrabat	0.0767	0.1	0.8	1.5
Wangotal. (2019b)	Gaitaptimizedsuimmer	0.4042	0.40	1.0	2.0
Wang et al. (2021)	Robotic larval zebrafirh Median finned-robot	0.133 0.353	0.00 4 3 0.58	31 0.61	83 1.5
Won ot al. (2018) Whito ot al. (2020)	Tunabat Flox	1.17	0.255	4.60	2.0
White (2022)	Tunabat Prototype	0.64	0.4064	1.6	8.0
Wuotal. (2015)	Robotic Erax Nocius	0.46	0.614	0.75	1.55
Nio et al. (2020)	Wire-driven rabatic firh	0.43	0.506	0.84	2.0
Yu & Tan (2015)	Postaral fin-propolled firh	0.71	0.68	1.04	3.5
Yu ot al. (2016a)	Single-mater-actuated firh	2.05	0.72	2.8	4.65
Yuotal. (2016b)	Loaping robotic dolphin	1.14	0.37	3.1	8.0
Yu et al. (2019)	Loaping robotic dolphin	2.11	0.72	2.93	4.65
Zhangotal. (2013)	Wire-driven rabatic firk	0.365	0.555	0.66	1.0
Zhang et al. (2017)	Wire-driven rabatic firh	0.67	0.31	2.15	3.0
Zhang et al. (2018)	Wire-driven rabatic fürh	1.02	0.31	1.4 4.00	2.0 14.8
Zhu ot al. (2019)	Tunabat	1.02	0.255	4.00	14.0

Reference	Description	Speed (m/s)	Body Length, BL (m)	Speed (BL/s)	Actuation Frequency (Hz)	Power (W)	Work per Meter (J/m)	Mass (kg)	COT (J/kg/m)
Berlinger er al. (2021)	Finbot	0.122	0.160	0.763	4.25	3.3	27	0.15	180
Bujard et al. (2021)	Robotic squid	0.26	0.266	0.98	9.0	0.09	0.4	0.380	0.93
Chen et al. (2015)	IPMC robotic cownose ray	0.007	0.21	0.034	0.157	2.0	280	0.119	2354
Chen et al. (2021)	Leaping fish bot	1.88	0.264	7.12	15.04	89	47	0.350	135
Christianson et al. (2018)	DEA robotic leptocephali	0.0019	0.22	0.0086	0.33	0.020	10.5	0.0251	419
Christianson et al. (2019)	DEA robotic jellyfish	0.0032	0.163	0.020	0.2	0.25	78	0.23	340
Cianchetti et al. (2015)	OCTOPUS	0.05	0.17	0.3	0.75	2.6	53	3.0	18
Erturk (2015)	MFC piezoelectric fish	0.075	0.243	0.31	5.0	1.4	19	n/a	n/a
Fujiwara & Yamaguchi (2017)	Single-motor-actuated fish	0.58	0.345	1.7	16.0	20.4	35	0.597	59.0
Kumph (2000)	Robopike	0.09	0.82	0.1	1.0	8.5	94	n/a	n/a
Kwak & Bae (2017)	Robotic water beetle	0.117	0.095	1.2	1.3	0.66	5.7	0.02265	250
Li et al. (2017)	Electro-ionic robotic fish	0.135	0.093	1.5	5.0	0.024	0.18	0.0425	4.18
Liu & Curet (2018)	KnifeBot	0.325	0.462	0.703	3.0	2.55	7.85	n/a	n/a
Long Jr. et al. (2006)	Madeleine	0.74	0.78	0.95	6.0	58.3	79	24.4	3.2
Mazlan (2015)	Robosalmon	0.143	0.90	0.16	1.0	5.4	37.8	4.30	8.8
Paschal et al. (2017)	Reconfigurable armed robot	0.1	0.6	0.2	2.0	4.51	45	2.1	21
Pham et al. (2019)	Pectoral fin-propelled robot	0.231	0.4	0.58	0.75	0.102	0.44	1.059	0.42
Sfakiotakis et al. (2015)	Robotic octopus	0.0986	0.38	0.26	0.9	3.83	38.8	2.68	14.5
Shintake et al. (2018)	DEA robotic fish	0.0372	0.15	0.25	0.75	0.92	25	0.0044	5621
Shintake et al. (2020)	Tensegrity trout robot	0.23	0.400	0.58	3.0	1.9	8.3	0.102	81.0
Villanueva et al. (2011)	Robojelly	0.0542	0.6	0.1	0.5	17.0	314	0.242	1296
Villanueva et al. (2013)	Cyro	0.0847	0.316	0.268	0.12	70.0	826	76.0	11
Wang et al. (2010)	SPC-3 UUV	1.87	1.6	1.2	2.5	194.0	104	n/a	n/a
Wang et al. (2021)	Robotic larval zebrafish	0.133	0.0043	31	83	4.8E-05	3.6E-04	1.535E-06	235
White et al. (2020)	Tunabot Flex	1.17	0.255	4.60	8.0	4.10	3.50	0.190	18.4
White (2022)	Tunabot Prototype	0.64	0.4064	1.6	8.0	10.8	16.9	0.90	18.8
Yu et al. (2016a)	Single-motor-actuated fish	1.14	0.37	3.1	8.0	25.6	22.5	n/a	n/a
Zhong et al. (2017)	Wire-driven robotic fish	0.67	0.31	2.2	3.0	5.6	8.3	0.5	17
Zhu et al. (2019)	Tunabot	1.02	0.255	4.00	14.8	8.67	8.50	0.306	27.8

Why am I here?

Using biology to inspire new solution pathways for fast, efficient underwater robots



Towards a Mission-Configurable Stealth Underwater Batoid

ONR MURI Program Manager: Dr R. Brizzolara

Bio-inspired flexible propulsors for fast, efficient swimming: What physics are we missing?

ONR MURI Program Manager: Dr R. Brizzolara











TUNABOT

High Speed <u>And</u> High Efficiency

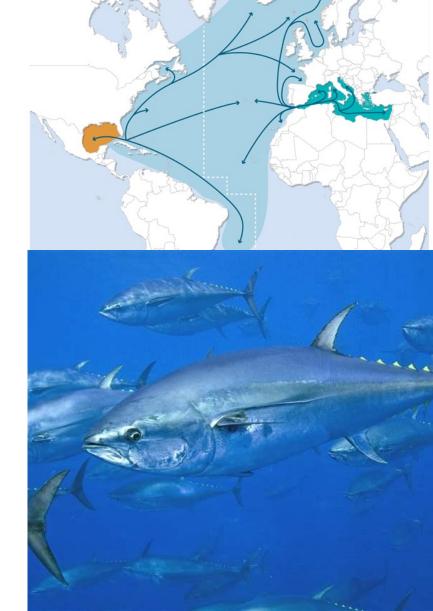


Tuna: biology and anatomy

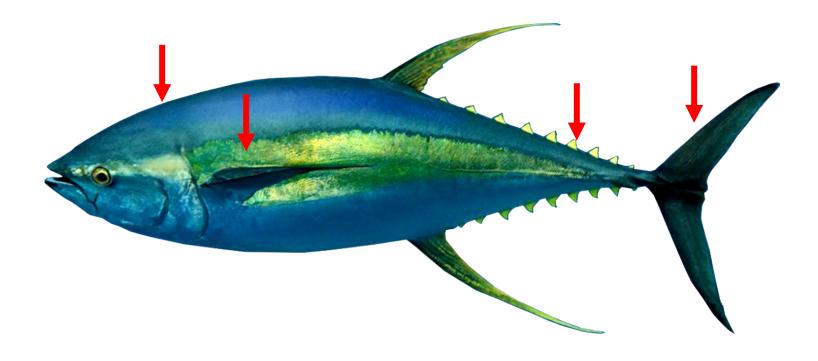
- Atlantic Bluefin tunas migrate across oceans
- Eastern and western populations mix for feeding but not breeding
- Spawn in Mediterranean and gulf of mexico
- Bluefin grow large (over 1000 lbs) and can sometimes sell for over \$1.5 milion per fish.

At Least 2 Populations of Atlantic Bluefin Tuna: Highly Migratory and Highly Mixed

Western and eastern bluefin mix to feed but separate to breed



Tuna: biology and anatomy



- Key features of tuna:
 - streamlined shape
 - lunate high-aspect ratio tail
 - wing-like pectoral fins
 - finlets
 - caudal peduncle and keel

Research Objectives

- 1. Study <u>high-performance</u> fish swimming using bio-inspired research platforms
 - Yellowfin tuna (Thunnus albacares)

High speed: High efficiency: $COT = \frac{Power}{Mass \cdot Speed}$ Body Lengths per second (BL/s) Cost of Transport (J/kg/m)

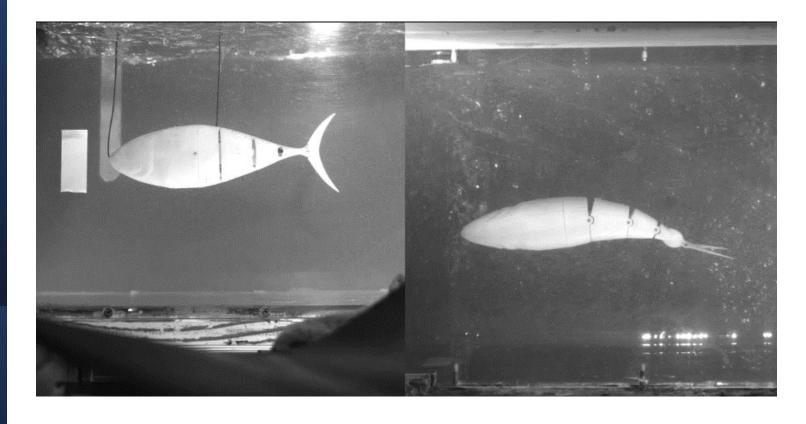
2. <u>Close</u> the performance gap between biology and robotic systems



Tunabot Flex Swimming Performance

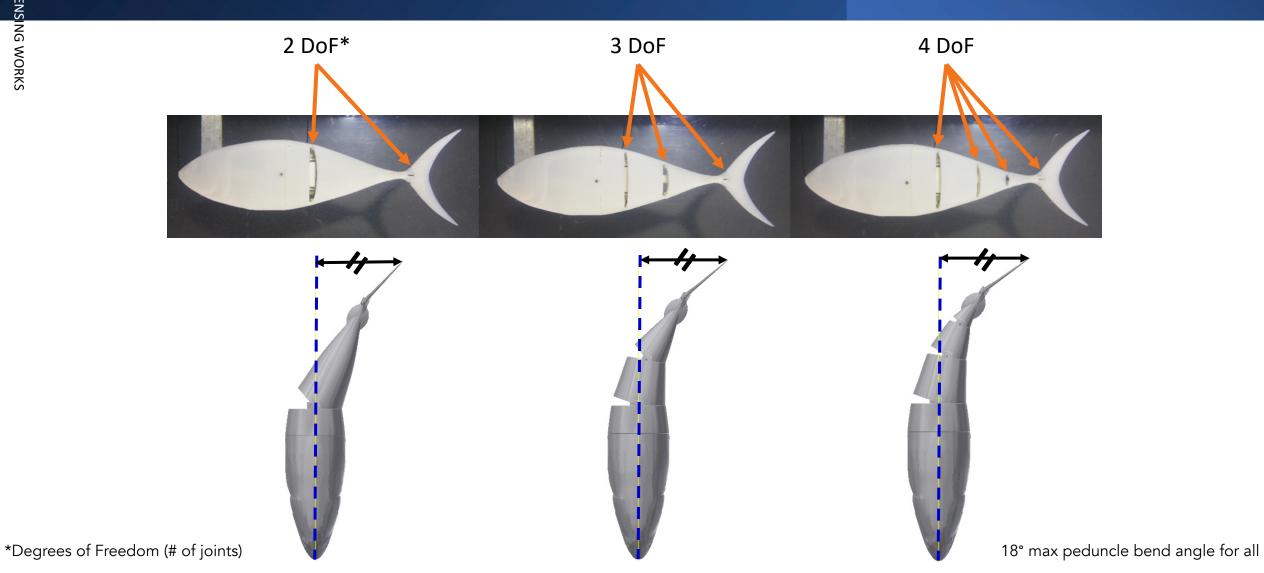
Lateral View

Ventral View

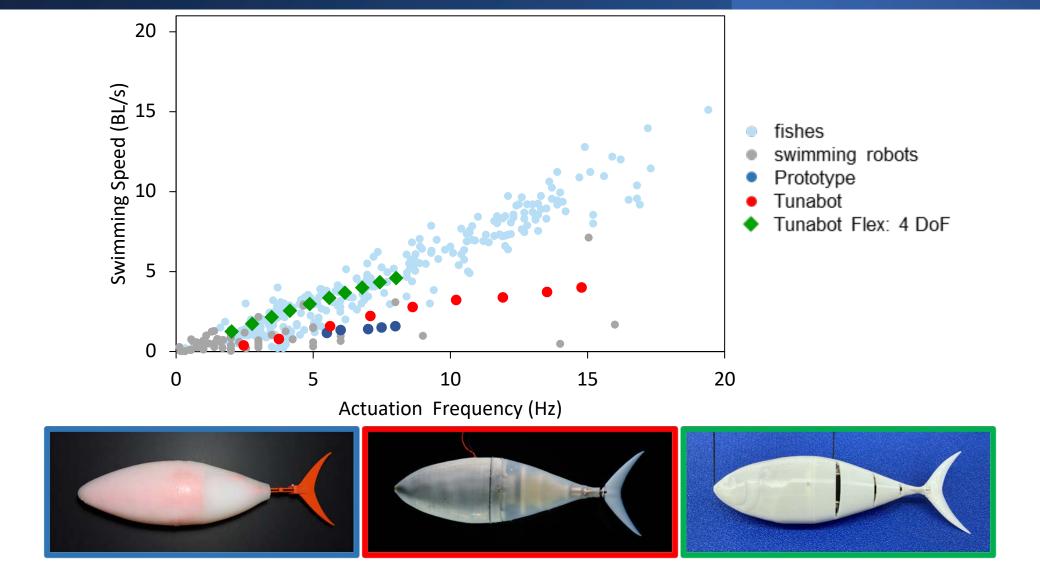


Lauder Lab flow tank, 4.6 BL/s, 8.0 Hz, 0.57x playback speed

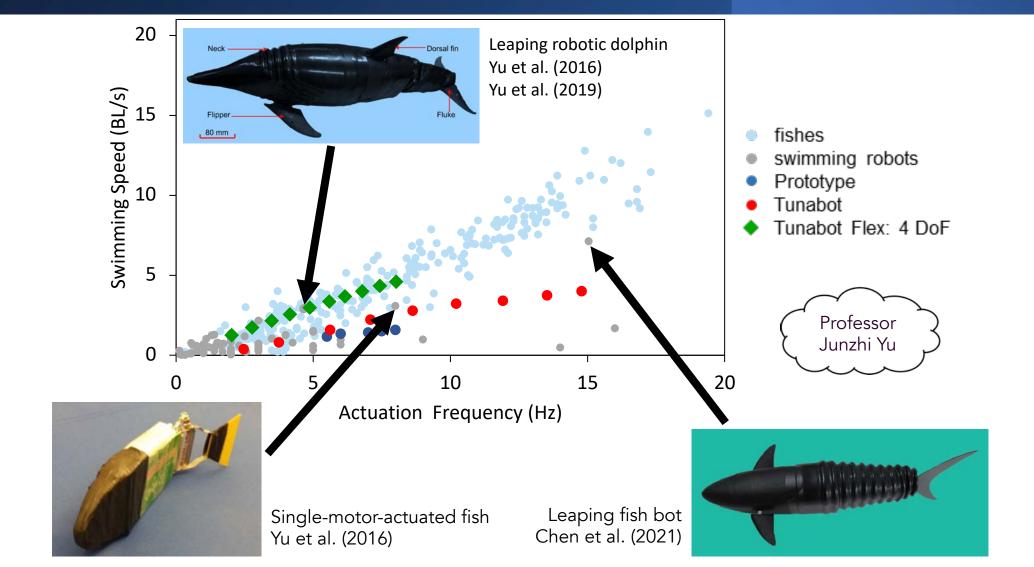
Tunabot Flex Platform Design



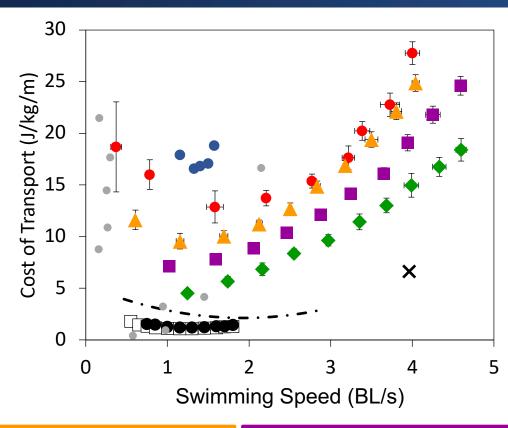
Performance Space Speed & Frequency



Performance Space Speed & Frequency



Performance Space Cost of Transport



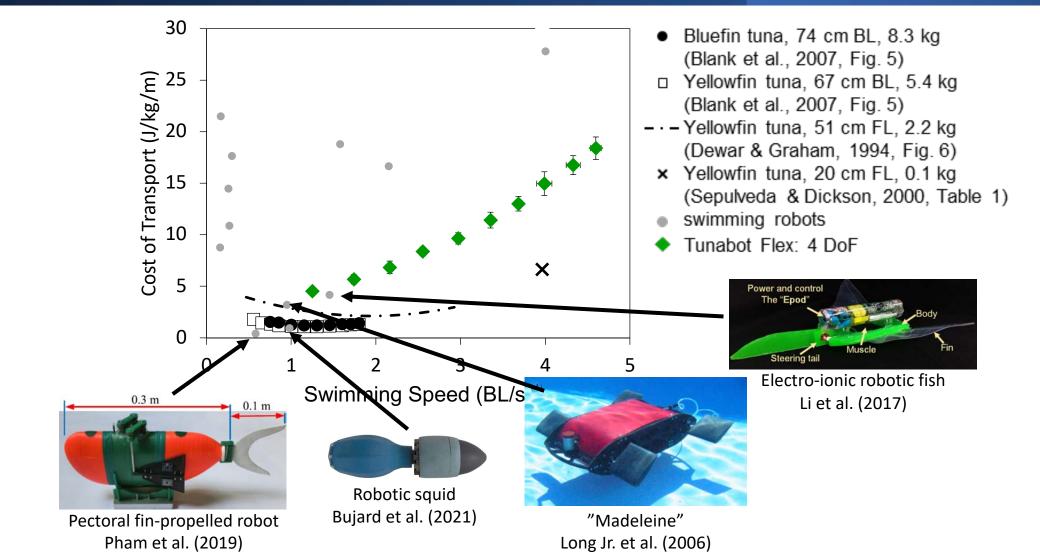
- Bluefin tuna, 74 cm BL, 8.3 kg (Blank et al., 2007, Fig. 5)
- Yellowfin tuna, 67 cm BL, 5.4 kg (Blank et al., 2007, Fig. 5)
- · · Yellowfin tuna, 51 cm FL, 2.2 kg (Dewar & Graham, 1994, Fig. 6)
- Yellowfin tuna, 20 cm FL, 0.1 kg (Sepulveda & Dickson, 2000, Table 1)
- swimming robots
- Prototype
- Tunabot
- Tunabot Flex: 2 DoF
- Tunabot Flex: 3 DoF
- Tunabot Flex: 4 DoF



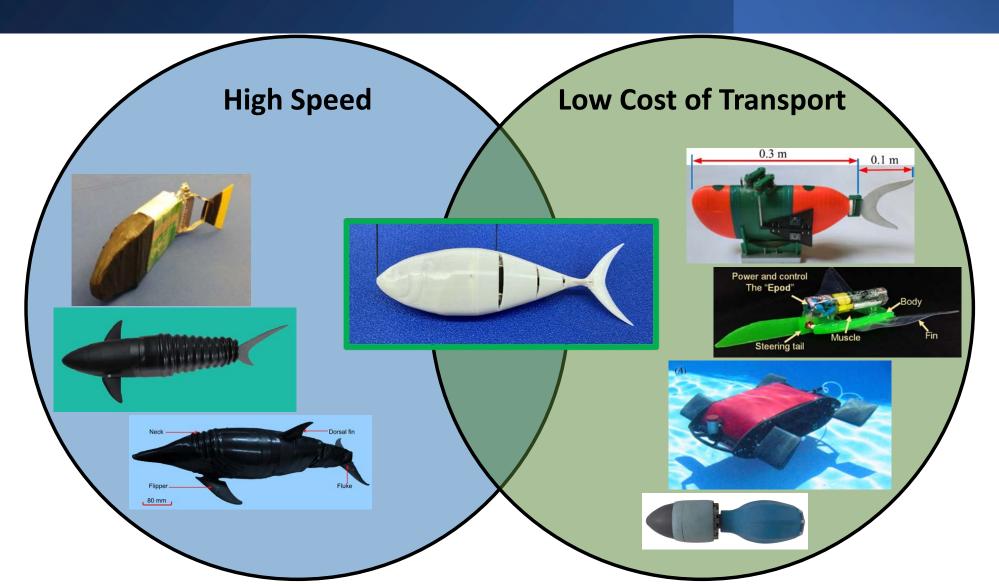




Performance Space Cost of Transport

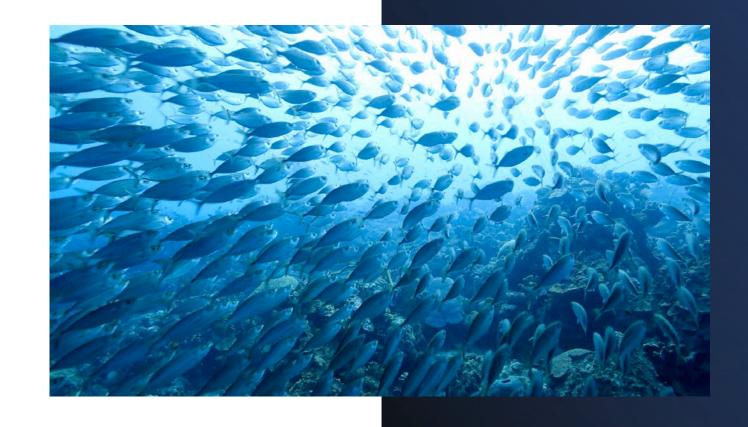


State of the Field High Speed <u>AND</u> High Efficiency



Fish Schooling

• Simultaneously surveying more area, more intelligently



Revealing the Hydrodynamic Principles of Three-Dimensional Fish Schools: From Biology to Schooling Robotics

Principal Investigator Keith Moored, Lehigh University, kmoored@lehigh.edu

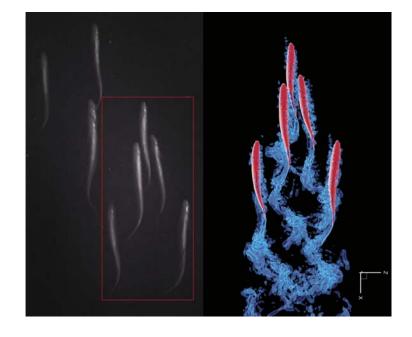








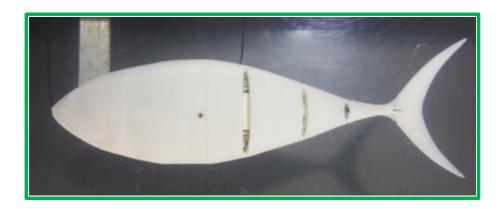
Co-Principal Investigators
George Lauder, Harvard University
Radhika Nagpal, Princeton University
Hilary Bart-Smith, University of Virginia
Daniel Quinn, University of Virginia
Haibo Dong, University of Virginia



BlueSwarm: bio-robots with decentralized schooling control

- Fish-inspired robot swarm
- Variable collective behaviors depending on mission requirements
- Berlinger et al. (2021) doi:10.1126/scirobotics. abd866





High-performance + schooling control

FINAL THOUGHTS

- This is a challenging problem and exciting: lots of questions
 - Can current technologies be adapted and expanded to explore all oceanic zones?
 - Will we require new technologies and approaches?
 - Is bio-inspired a potential solution path? Soft-systems?
 - Synergies between sensor development and platform and platform control development (control co-design)?
 - Energetics costs?
 - Platform range
 - Recharging implications (Charging stations? On-board power generation?)
 - Economics?